Economic evaluation of Nearly Zero Energy Cities

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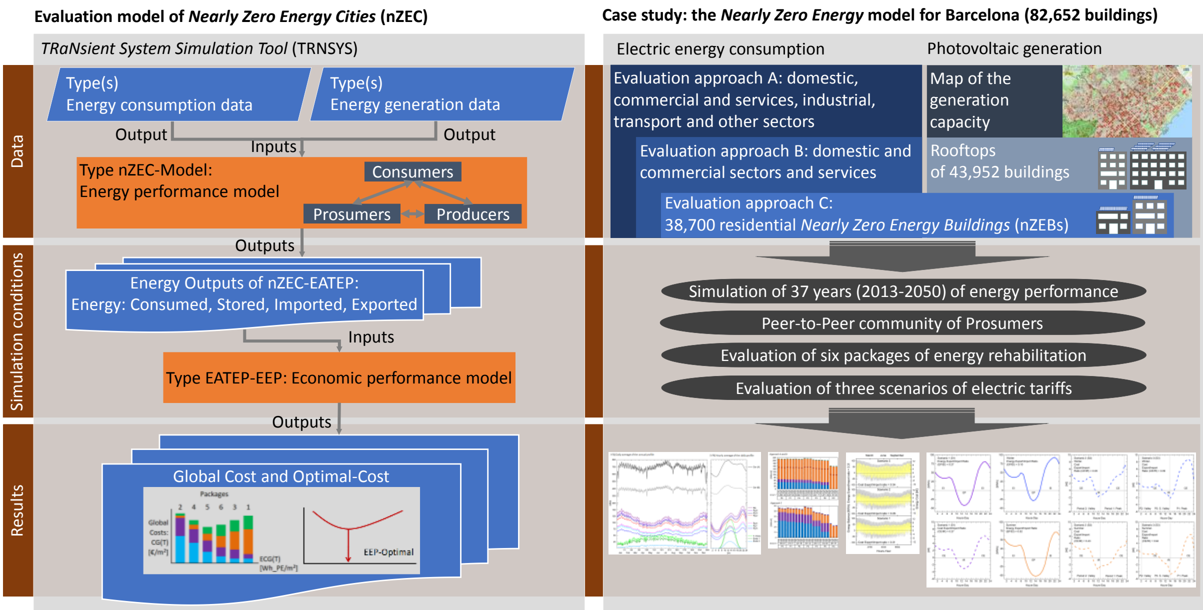
Graphical abstract



Abstract

As a contribution to the study of the urban energy transition, this paper proposes a novel model of energy-economic evaluation of the cities self-sufficiency and presents its application in the form of a case study. The objective of this study was to analyse the scope of the investment in the photovoltaic self-consumption of buildings in order to promote the creation of Prosumers communities within the cities. The operation of this model is based on the scalability of the *Nearly Zero Energy* concept from buildings to cities and seeks to evaluate *Nearly Zero Energy Cities* (nZEC): cities made up of *Nearly Zero Energy Buildings* (nZEB) and other installations of distributed generation to cover their energy demand by use of local renewable resources to the detriment of external resources. By using public data, we apply this model with the aim of economically evaluating the investment of six packages of energy rehabilitation and photovoltaic self-consumption in 17% of the residential buildings (37,800) in the city of Barcelona. To do this, we simulated 37 years of electricity distribution among Consumers, Producers and a hypothetical *peer-*

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to-peer community of Prosumers during the period 2014-2050 in hourly time intervals. The results indicated that the photovoltaic self-consumption and the local markets of Prosumers help to reduce primary energy consumption, the energy costs, and the CO_2 emissions.

Keywords: Nearly Zero Energy Buildings (nZEB), Nearly Zero Energy Cities (nZEC), Urban energy transition, Photovoltaic self-consumption, Prosumer

Nomenclature			
Csr	Consumers	NZEB	Net Zero Energy Building
CEG(T)	Global Energy Cost	nZEC	Nearly Zero Energy City
CG(T)	Global Cost	P	Electric tariff period (P1, P2, P3)
CIG(T)	Global Investment Cost	Pg	Package: Set of EEM
CRG(T)	Global Running Cost	PCharge_γ(h)	Power charges
CsrS	Consumers with electric energy storage	Pdr	Producer (IPP, or utility generator)
EA	Electric energy endogenous available	PEU_γ (h)	Energy price
ECharge_γ(h)	Electric energy charges	Psr	Prosumer
ED	Electric energy demand	PsrS	Prosumers with electric energy storage
EEM	Energy Efficiency Measures	Rd(t)	Discount Rate,
EG	Electric energy generation	RI	Inflation Rate
EI	Electric energy imported	RR	Real Interest Rate
Endo	Endogenous electric energy consumed (Local)	t	Each of the years of T
EP	Electric energy exported	T	Economic evaluation period (Years of 8760 hours)
EPBD	Energy Performance of Buildings Directive	Tn	Lifespan
ES	Electric energy storage	Type	Subroutine of TRNSYS
EValue_γ(h)	Economic value of the energy flow	UTC	Urban Energy Transition
Exo	Exogenous electric energy (external of the nZEC)	VF_j(T)	Final value of the Component
NZEB	Net Zero Energy Building		

1. Introduction

Cities are home to more than half of the world population and this has an impact in that 70% of the world energy consumption and greenhouse gas emissions are concentrated in these urban areas [1]. Urbanization has led to an increase in the proportion of urban energy use of the total global primary energy supply [2]. In view of the fact that the projections up until 2050 indicate that the world population will be 30% larger [3], and that 68% of it will be urban [4], cities play a fundamental role in the process of energy transition [5]. This process requires a structural change in the world energy sector, moving towards the increase of energy efficiency and the consumption of renewable energy resources, and the reduction of the consumption of fossil energy resources [6,7]. In this sense, the solar resource plays a notable role, given the uniformity of its distribution on a global scale [8]. Although each economic region of the world has different drivers in this transition [6,9], there is a general consensus to focus on working towards a higher level of effectiveness when it comes to energy consumption in various areas such as industry, transport and building (housing, commercial and services) [10]; In this sense, within the framework of the Paris agreement, the European Union (EU) recognizes the importance of the role of cities in moving towards a low carbon economy [11].

A high percentage of the energy demand of cities is concentrated in their buildings [10] and in order to promote the increase of energy efficiency, herein exists the greatest potential for savings [2]. Effective energy transition from the cities implies Urban Energy Transition (UET), therefore, deepening the efforts in promoting Distributed Generation (DG) and reorientating the consumption and energy supply of buildings and communities (buildings group). Thus, it is necessary to concentrate economic resources in the investment of Energy Efficiency Measures (EEM) and self-consumption systems [12,13]; as well as facilitating the creation of the Prosumer figure [14]: Consumers who, due to their self-consumption capacity can, by virtue of the regulatory conditions of the electrical systems and market, export energy to the distribution grid [15]. From the integration of renewable energies in buildings and communities, the zero energy concept is understood as the frontier of energy efficiency, energy self-sufficiency and urban sustainability [16,17]. This concept can be defined in general terms as the reduction of primary energy consumption and the generation of energy in situ from renewable resources in facilities or *focuses of consumption* by means of investment in EEM and self-consumption technologies. When the amount of energy required is less than the quantity generated in situ, and regardless of any energy storage that may exist, these *focuses of energy consumption* can export their energy surpluses to the grid.

In this sense in [18–20] the *Net* and *Nearly Zero Energy* concepts are analysed as a sequence of steps towards buildings' self-consumption. Adapting this analysis to the definition of UET, *Nearly Zero Energy* can be an initial step for a net balance or *Net Zero Energy*, and this can also be a previous step towards the total exportation of energy surpluses or *Net Plus Energy* of cities. In this context, in order to contribute to the study of the reduction of negative environmental externalities that causes the high consumption of fossil energy resources in cities, this paper aims to propose an energy-economic evaluation model to study the energy self-sufficiency of cities. With this, we seek to verify the hypothesis that the use of local solar resources, through the photovoltaic self-sufficiency of the buildings, and the distribution of electrical energy among Prosumers, Consumers and Producers, helping to reduce the consumption of primary energy together with lowering energy costs and CO_2 emissions.

The proposed evaluation model, called nZEC-EATEP, is novel and replicable in any city due to being based on the scalability of the concept *Nearly Zero Energy* from a building (Nearly Zero Energy Buildings, nZEB) to city level (Nearly Zero Energy City, nZEC). Regarding to the evaluation of nZEC, [21,22] analyse the generation capacity of urban buildings to maintain the balance between that and their energy consumption. Faced with these proposals, nZEC-EATEP works within the *TRaNsient System Simulation Tool* (TRNSYS) and is the union of two independent models that can be fed with other models or software. The first of these independent models is an energy performance simulation model of nZECs, called nZEC-Model. The second one is the economic evaluation model of the energy systems *Economic Assessment Tool of Energy Projects* (EATEP) proposed in [23]. The operation of nZEC-EATEP consists of the evaluation of the costs in reducing the energy consumption and the use of local renewable resources (endogenous energy) and thus reducing the use of external resources (exogenous energy). Through this design the model allows: *i)* to simulate the energy performance of the distribution of energy between Producers, Prosumers and Consumers; *ii)* evaluate different packages of EEM at a city level and self-consumption to calculate, at the same level, the Global Cost and Optimal-Cost indicators presented in the *Energy Performance of Buildings Directive* (EPBD) of the European Union [24,25]; and *iii)* configure the energy distribution under different market models.

Using public data obtained by local energy agencies, the nZEC-EATEP was applied to study the energy self-sufficiency of Barcelona (Spain). In this study we evaluate the costs to take advantage of the city's photovoltaic (PV) self-sufficiency capacity by analysing 82,652 of its buildings, the city's electricity consumption in three approaches, and three electricity tariff scenarios. The analysis of these buildings included: *i)* the capacity of energy saving and PV self-consumption of 38,700 residential buildings (46.82%), defining them as nZEBs in six energy rehabilitation Packages; *ii)* the peer-to-peer distribution of electrical energy among these nZEBs, defining them as Prosumers; and *iii)* the PV generation capacity of the remaining 43,952 buildings (53.18%). Specifically, the study of this nZEC model for Barcelona sought to achieve three objectives: *i)* to calculate the cost and primary energy savings that these packages allow; *ii)* to determine the package that allows the greatest reduction in primary energy consumption at the lowest cost; and *iii)* identify which current electricity tariff (Spain) is more favourable for the investment of these energy self-consumption measures.

The concept of economic evaluation is broad and includes the analysis of financial indicators on the return on investment. At the scale of a city, the evaluation of a Zero Energy model in this study is based on the calculation of the Global Cost and Optimal-Cost indicators without analysing the returns of the possible nZEB investments that residential Consumers could make to become Prosumers. Similarly, the scope of this study does not address the investment decisions in energy rehabilitation measures that public entities make to reduce their energy consumption. Likewise, this study does not address the scope of an established budget to reduce the energy consumption of buildings in a city. However, in this line of research, the works of [26,27] do study the investments in energy rehabilitation of buildings using decision models. Our work focuses on the study of the *total* self-consumption capacity of cities.

The document is divided as follows: in the first instance, a review of the cutting-edge concept *Nearly Zero Energy* applied at a city level in terms of energy self-consumption is presented; subsequently, the proposed evaluation model is described; and finally, the evaluation of a nZEC-Model for Barcelona is presented, together with the results and conclusions obtained.

2. Literature review

As mentioned above, the Nearly Zero Energy City[1,2] concept is the frontier of energy self-consumption, and this is based on the use of renewable energy resources in buildings [28]. The literature about nZEBs on this topic is extensive [29]. The nZEBs are a link in the Smart Cities development work chain [30,31], although the growth in the number of nZEBs in the urban electrical systems poses challenges and benefits in maintaining of the grid [32,33]. In Europe, the evaluation of the nZEBs has been promoted by the EPBD. On a larger scale, [34,35] propose a circular exergy model as well as studies that may carry the net-zero concept to net-zero energy and net-zero exergy cities. On that same issue, [36] reports the increase of studies of this nature under the concept of energy autonomy in sustainable communities. In [37] the concept of a Cooperative Net Zero Energy Community is introduced. In isolated systems [38,39] analyse self-consumption on islands; and in this same way, [40,41] analyse the integration of renewable energies in islands through microgrid and Smart Grid technologies. And specifically regarding carbon emissions, [42,43] study the classification of cities with zero carbon emission composed of buildings with zero emissions.

At the level of evaluation of the Zero Energy city concept, [44] provides an overview of the existing assessment tools and methods, comparing their criteria and key parameters. Similarly, [45] reviews the crucial role of building performance simulation to reach building's zero energy status. [46] proposes an evaluation methodology for this purpose, based on the availability of geometry, building standards and useable data. [47] presents a development plan for the rehabilitation of groups of buildings to obtain a Zero Energy city. At these levels of evaluation, the generation in situ happens to be considered as DG in charge of Prosumers and Producers [48,49], which must cover the energy demand of other sectors such as transport, industry, commerce and services [16].

[1] A systematic search of the web pages of Web of Science and Scopus databases for the terms "nearly zero energy city", "net zero energy city", "nearly zero energy cities", "net zero energy cities", "zero energy city", and "zero energy cities" produced a result of 10 references.

[2] In this search several references were also identified on the development of technical solutions for the promotion of "net zero energy city districts" within the framework of the European project FP7 project RE-SIZED (Research Excellence for Solutions and Implementation of Net Zero Energy City Districts).

Likewise, the exchange of energy at these lower levels of the electric distribution implies the participation of these actors in local energy markets [50].

On the other hand, self-consumption is not understood without the presence of storage systems to support the intermittency of renewable energies and the lag that these energies have with respect to consumption curves. In this sense, [51,52] report benefits with the analysis of tariff systems for access to the grid. Benefits that, as indicated in [53,54], depend on the parameters of the Consumer's load profile and the size of this type of systems [55]. Regarding tariff systems or markets that can encourage investment in zero energy communities, [56] reports the benefits of dynamic price rates for PV self-consumption. Also, [57,58] validate the operation and benefits of peer-to-peer models in local markets. Finally, with respect to the case study in this paper, in [59] a real-time model of optimization of PV self-consumption with batteries is studied in real installations in Barcelona, which allows for an increase in the income from the export of surplus energy to the grid with a dynamic tariff.

3. Description of the evaluation model

The nZEC-EATEP model is the union of a simulation model of nZECs, called nZEC-Model, and the energy systems economic evaluation model EATEP. Its operation consists of the evaluation of the economic performance of the energy performance of the energy self-sufficiency process of cities. The process derived from the increase of DG and of services aggregates to the urban electrical system. Figure 1 conceptualizes the methodological basis of the nZEC-EATEP model, the UET. This model is as follows. First, *i-F1)*: the energy demand increases due to the increase of the urban population, and the consumption decreases in relation to the increase of the energy efficiency in the buildings and electrical grid. Then, *ii-F1)* as energy self-consumption becomes more present in buildings with the entry of nZEBs and NZEBs, the consumption of endogenous energy increases and decreases that of exogenous energy. Finally, *iii-F1)* the nZEC-EATEP allows for the stimulation of the energy self-consumption of nZECs and the calculation of the current value of the investment, operation and energy costs.

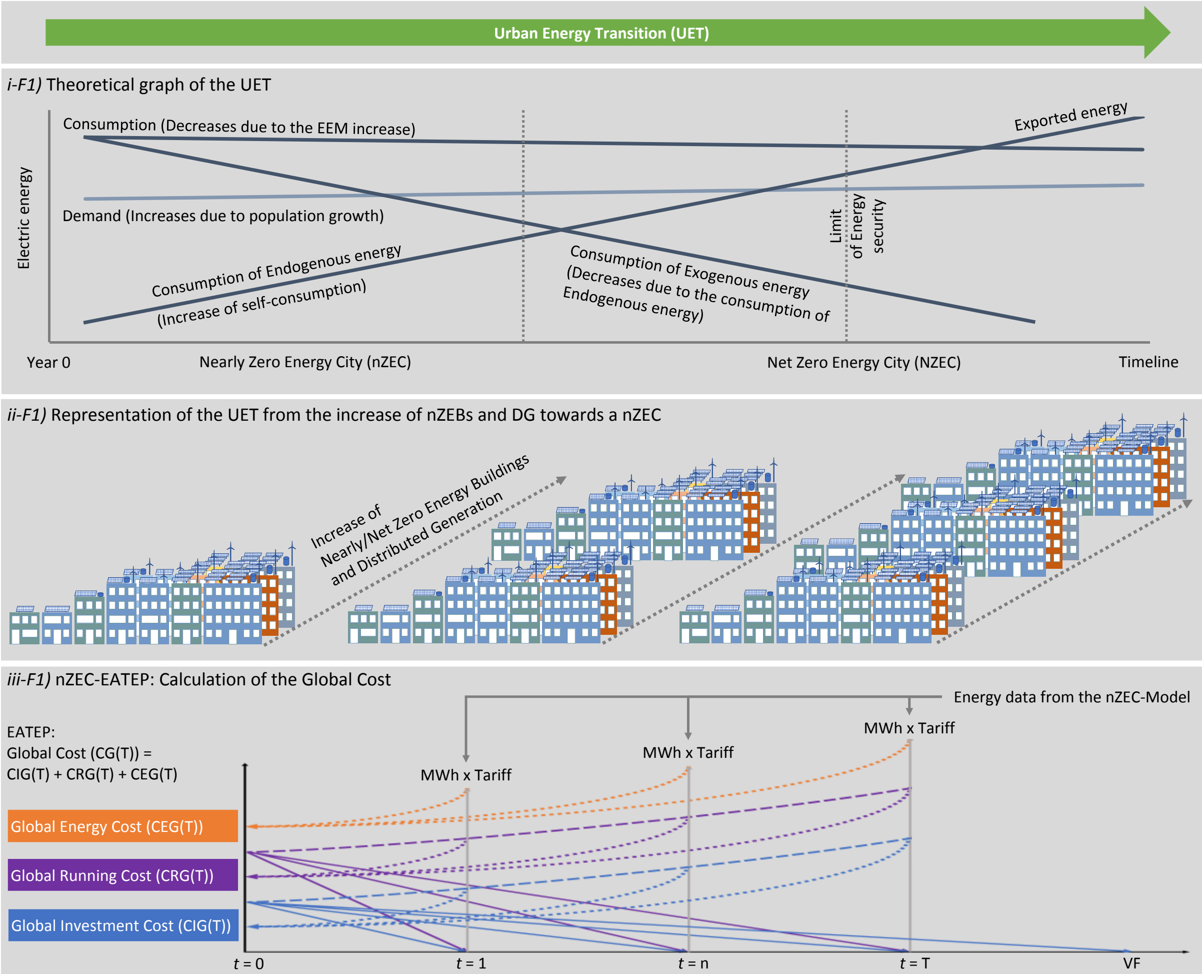

Figure 1. Graphic representation of the Urban Energy Transition (UET), as a conceptualization of the methodological basis of the nZEC-EATEP model.

The analysis of energy performance in the nZEC-Model refers to the simulation and accounting of energy flows exchanged between Consumers (Consumer installations within the city), Prosumers (nZEBs) and Producers (DG systems) to maintain the energy balance between the energy demanded by the city and the energy that is endogenous and exogenous to it in hourly time intervals. The energy demanded is the energy demanded by Consumers and Prosumers, the endogenous energy is the energy generated by Prosumers and Producers, and the exogenous energy is the energy generated by outside the urban area of the city.

On the other hand, the economic performance evaluation, carried out in the EATEP, is the accounting of the investment costs of the EEM, self-consumption and DG, and of the costs and revenues produced by the exchange of the energy flows. This tool can evaluate different packages of self-consumption and EEM in order to calculate the Global Cost at a city level (net present value of the initial investment and the costs of component replacement, maintenance and energy) and

Optimal-Cost (graphic identification of the package that has the lowest global cost and allows for the reduction of the primary energy consumption of the city).

The nZEC-EATEP model was built in TRNSYS. Figure 2 presents the operation of the nZEC-Model. *i-F2)* indicates the operation of the model in the TRNSYS subroutines (Types) wherein are included Types of generation and energy demand of Producers, Prosumers and Consumers that deliver data (Inputs) to the nZEC-Model, whose results (Outputs) feed the EATEP, and where this Type delivers the economic and financial results for all packages of evaluated energy efficiency and self-consumption measures. *ii-F2)* presents the conceptual functioning of the nZEC-Model, wherein its algorithm seeks to maintain the energy balance between the endogenous energy of the nZEC and the energy exogenous to it. *iii-F2)* presents this algorithm in a general way. *iv-F2)* and *v-F2)* describe, respectively, the structure of the cash flows calculated in the EATEP and the indicators of this tool. The operation of the energy simulation model and the economic evaluation model are described below.

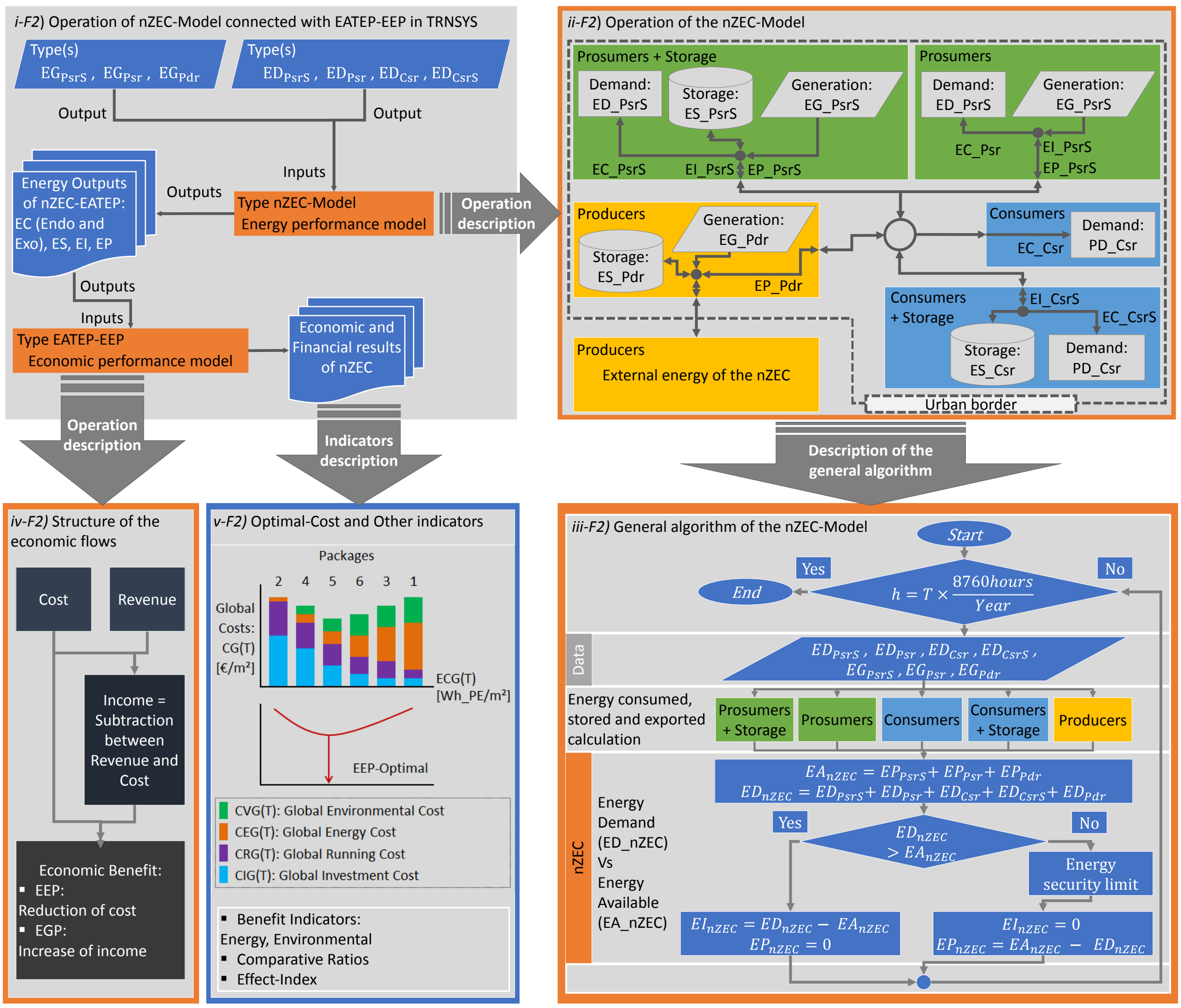

Figure 2. Graphic description of the nZEC-EATEP model. Note: *iv-F2)* and *v-F2)* adapted from [23].

3.1. Energy performance evaluation of Nearly Zero Energy Cities

As mentioned above, the nZEC-Model simulates the energy balance in the nZEC in hourly intervals for any period of economic evaluation (T). Based on the energy demand of Prosumers and Consumers, the availability of endogenous energy and the following energy distribution conditions, the amount of exogenous energy needed to maintain the energy balance at each time step is determined: *i)* The exchange of energy works in a basic state without conditions of energy markets, which can be included from another subroutine; *ii)* Endogenous energy is consumed as a priority to exogenous energy, first of all meeting the demand of Prosumers and then that of Consumers; *iii)* The self-consumption (ECG) and consumption of energy storage (ECS) are priorities, in this order, so only energy is exported when the storage systems are full (Energy Storage Accumulated, ESA); *iv)* The importation of exogenous energy is the responsibility of the Producers.

From these conditions, the destination of the available energy (EA) in the nZEC is consumed as imported energy (EI) in the following order of priority: Csr, CsrS, Psr, PsrS. Subsequently, Pdr imports energy from the outside of the nZEC. Details are as follows:

- Consumers (Csr): Psr (Case1); PsrS (Case2); CsrS (Case3); or Pdr (Case4).

$$EI_{Csr} = \begin{cases} EI_{Csr} = EP_{Psr}, & Case_1 \rightarrow ED_{Csr} \leq EP_{Psr} \\ EI_{Csr} = EP_{Psr} + EP_{PsrS}, & Case_2 \rightarrow ED_{Csr} \leq EP_{Psr} + EP_{PsrS} \\ EI_{Csr} = EP_{Psr} + EP_{PsrS} + EP_{CsrS}, & Case_3 \rightarrow ED_{Csr} \leq EP_{Psr} + EP_{PsrS} + EP_{CsrS} \\ EI_{Csr} = EP_{Psr} + EP_{PsrS} + EP_{CsrS} + EP_{Pdr}, & Case_4 \rightarrow ED_{Csr} > EP_{Psr} + EP_{PsrS} + EP_{CsrS} \end{cases} \tag{1}$$

- Consumers + Storage (CsrS): Psr (Case1); or PsrS (Case2) and Pdr (Case3).

$$EI_{CsrS} = \begin{cases} EI_{CsrS} = EP_{Psr} - EC_{Csr}, & Case_1 \rightarrow EC_{CsrS} - ECS_{CsrS} \leq EP_{Psr} - EC_{Csr} \\ EI_{CsrS} = EP_{Psr} + EP_{PsrS} - EC_{Csr}, & Case_2 \rightarrow EC_{CsrS} - ECS_{CsrS} \leq EP_{Psr} + EP_{PsrS} - EC_{Csr} \\ EI_{CsrS} = EP_{Psr} + EP_{PsrS} + EP_{Pdr} - EC_{Csr}, & Case_3 \rightarrow EC_{CsrS} - ECS_{CsrS} > EP_{Psr} + EP_{PsrS} - EC_{Csr} \end{cases} \tag{2}$$

- Prosumers (Psr): PsrS (Case1); PsrS (Case2); or Pdr after Csr and CsrS (Case4).

$$EI_{Psr} = \begin{cases} EI_{Psr} = EP_{PsrS} - (EI_{Csr} + EI_{CsrS}), & Case_1 \rightarrow EC_{Psr} - ECG_{Psr} \leq EP_{PsrS} - (EI_{Csr} + EI_{CsrS}) \\ EI_{Psr} = EP_{PsrS} + EP_{Pdr} - (EI_{Csr} + EI_{CsrS}), & Case_2 \rightarrow EC_{Psr} - ECG_{Psr} > EP_{PsrS} - (EI_{Csr} + EI_{CsrS}) \\ EI_{Psr} = EP_{PsrS} + EP_{CsrS} - EI_{Csr}, & Case_3 \rightarrow EC_{Psr} - ECG_{Psr} \leq EP_{PsrS} + EP_{CsrS} - EI_{Csr} \\ EI_{Psr} = EP_{PsrS} + EP_{CsrS} + EP_{Pdr} - EI_{Csr}, & Case_4 \rightarrow EC_{Psr} - ECG_{Psr} > EP_{PsrS} + EP_{CsrS} - EI_{Csr} \end{cases} \tag{3}$$

- Prosumers + Storage (PsrS): Psr after Csr and CsrS (Case1); Psr and Pdr after Csr and CsrS (Case2); Psr and CsrS after Csr (Case3); or Psr, CsrS and Pdr after Csr (Case4).

$$EI_{PsrS} = \begin{cases} EI_{PsrS} = EP_{Psr} - (EI_{Csr} + EI_{CsrS}), & Case_1 \rightarrow EC_{PsrS} - ECG_{PsrS} - ECS_{PsrS} \leq EP_{Psr} - (EI_{Csr} + EI_{CsrS}) \\ EI_{PsrS} = EP_{Psr} + EP_{Pdr} - (EI_{Csr} + EI_{CsrS}), & Case_2 \rightarrow EC_{PsrS} - ECG_{Psr} - ECS_{PsrS} > EP_{Psr} - (EI_{Csr} + EI_{CsrS}) \\ EI_{PsrS} = EP_{Psr} + EP_{CsrS} - EI_{Csr}, & Case_3 \rightarrow EC_{Psr} - ECG_{Psr} - ECS_{PsrS} \leq EP_{Psr} + EP_{CsrS} - EI_{Csr} \\ EI_{PsrS} = EP_{Psr} + EP_{CsrS} + EP_{Pdr} - EI_{Csr}, & Case_4 \rightarrow EC_{Psr} - ECG_{Psr} - ECS_{PsrS} > EP_{Psr} + EP_{CsrS} - EI_{Csr} \end{cases} \tag{4}$$

- Producers (Pdr): When the energy to be exported is greater than the energy generated locally (Case1); or when it is greater than locally generated and stored (Case2).

$$EI_{Pdr} = EI_{nZEC} = \begin{cases} EI_{Pdr} = EG_{Pdr}, & Case_1 \rightarrow EP_{Pdr} \leq EG_{Pdr} \\ EI_{Pdr} = EG_{Pdr} + ESA_{Pdr}, & Case_2 \rightarrow EP_{Pdr} \leq EG_{Pdr} + ESA_{Pdr} \end{cases} \tag{5}$$

3.2. Economic performance evaluation of Nearly Zero Energy Cities

The economic evaluation of the nZEC is carried out with the subroutines that make up the EATEP in its configuration V: The Type EATEP-EEP to evaluate the nZEBs and/or the NZEBs and the nZEC itself, and the Type EATEP-EGP to evaluate the DG systems belonging to the Producers. The main indicator of the EATEP is the Global Cost (CG(T)), equations (6) and (7); its result is the net present value of three groups of costs for Prosumers (Psr), Consumers (Csr) and Producers (Pdr): Global Investment Cost (CIG(T)), Global Running Cost (CRG(T)) and Global Energy Cost (CEG(T)). CIG(T) and CRG(T) are calculated with equations (8) and (10) respectively, from the investment and Maintenance Cost (CM) of energy measures (Components (*j*)). In the calculation of CIG(T), CII(T) is the Initial Investment Cost of the Component *j*, and CI(Tn) is the replacement cost where *t* is equal to Lifespan (Tn) of each Component *j*, and VF_j(T) is the final value in the year T (equation (9) [24]). CEG(T), equations (11), (12) and (13), depend on the hourly energy flows (FE_γ(h)), the tariffs for access to the distribution grids (PCharge_γ(h) to the power charges of access, and ECharge_γ(h) to the energy charges), and the economic value of the flow (EValue_γ(h)) calculated based on market energy prices (PEU_γ (h)). In CEG(T), the income received by the Prosumers when exporting their energy surpluses to the grid are calculated as negative costs which help reduce CG(T). Thus, EValue_γ(h)) depends on whether FE_γ(h) is an amount of energy imported (consumed) or exported –equation (13)–: if it is imported, EValue_γ(h) is calculated as a cost, and if it is exported, it is calculated as a negative cost. Each of the future annual costs were updated to the initial year using the Discount Rate, Rd(t). This rate, equation (14), depends on the Real Interest Rate (*RR*), equation (15), and Inflation Rate (*RI*).

$$CG_{(nZEC)}(T) = CG_{(Psr)}(T) + CG_{(Csr)}(T) + CG_{(Pdr)}(T) \tag{6}$$

$$CG(T)_{(Psr,Csr,Pdr)} = CIG(T)_{(Psr,Csr,Pdr)} + CRG(T)_{(Psr,Csr,Pdr)} + CEG(T)_{(Psr,Csr,Pdr)} \tag{7}$$

$$CIG_{(Psr,Csr,Pdr)}(\mathrm{T}) = \sum_{j}\left[CII(t=0)_j + \left(\sum_{t=1}^{T} CI_j(Tn_j) \times Rd_t(j)\right) - VF_j(T)\right] \quad (8)$$

$$VF_j(T) = VIC_j \times \left(1 + \frac{RX_j}{100}\right)^{(n_T(j) \times T_n(j))} \times \left[\frac{(n_T(j)+1) \times T_n(j) - T}{T_n(j)}\right] \times Rd_j(t) \quad (9)$$

$$CRG_{(Psr,Csr,Pdr)}(T) = \sum_{j}\left[\sum_{t=1}^{T} CR_j(t) \times Rd_t(j)\right] \quad (10)$$

$$CEG_{(Endo\_Psr,Csr)}(T) = \sum_{\gamma}\left[\sum_{h=1}^{h=T\times 8760 hours} \left(PCharge_\gamma(h) + EValue_\gamma(h)\right) \times Rd_\gamma(t)\right] \quad (11)$$

$$CEG_{(Exp\_Psr,Csr)}(T) = \sum_{\gamma}\left[\sum_{h=1}^{h=T\times 8760 hours} \left(PCharge_\gamma(h) + ECharge_\gamma(h) \times FE_\gamma(h) + EValue_\gamma(h)\right) \times Rd_\gamma(t)\right] \quad (12)$$

$$EValue_\gamma(h) = \begin{cases} FE_\gamma(h) \times PEU_\gamma(h), & If\ FE_\gamma(h)\ is\ imported \\ -FE_\gamma(h) \times PEU_\gamma(h), & If\ FE_\gamma(h)\ is\ exported \end{cases} \quad (13)$$

$$Rd_{\gamma,j}(t) = \frac{1}{(1 + RR/100)^t}\ [-] \quad (14)$$

$$RR = \frac{R - RI}{1 + (RI/100)}\ [\%] \quad (15)$$

4. Case study[3]: the Nearly Zero Energy model for Barcelona

Barcelona is a European city that is home to approximately 3.5% of the population of Spain. It is located on the coast of the Mediterranean Sea, covering an area of 102.159 km^2, and presents ideal conditions for the use of solar energy: it has on average 2,477 hours of sunshine per year, which represents an average daily solar radiation of 1,502 kWh/m^2 [60]. The city has opted for growth and development under the concept of *Smart City*, which has led to specific plans to achieve its energy self-sufficiency [60–62]. According to the annual report of its Energy Agency in 2014 [63], Barcelona consumed a total of 15,627 GWh of final energy, equivalent to 26,946.14 GWh of primary energy, distributed in its economic sectors as follows: commercial and services 34.09 %, domestic 28.11%, transport 25.65%, industry 11.54%, and other 0.61%. The entirety of this consumption comes from natural gas, nuclear energy and liquid fuels. 29.7% of the electric energy was generated in the city itself, 4,865 GWh, mainly in combined cycle plants and less than 1% in installations that take advantage of the local renewable resources.

Following the guidelines of the nZEC-EATEP, in this case study we analysed the energy performance of six Packages of combinations between EEM and PV self-consumption systems installed in a portion of the city's buildings. The objective of this evaluation was to discover the scope of the nZEBs investment and the economic participation of Prosumers in the energy balance and self-consumption of Barcelona. This was divided into *i)* three evaluation approaches, two based on the

[3] Several publications have reported the state of self-consumption in cities around the world: [71–73] in the United States, [74] in cities in Europe, [75] in cities in the Middle East, and [76] in Asian cities.

variation of consumption of base energy for Consumers in the initial year, and one on the analysis of Prosumers; and *ii)* in three tariff scenarios with and without daily hourly discrimination to determine which combination of these energy measures would allow the reduction of the primary energy of the city at the lowest possible cost. The energy and economic characteristics of these six Packages were defined by comparing the information of two groups of public data of the buildings of Barcelona (data obtained from public administration entities in Barcelona and the Spanish Autonomous Community of Catalonia). The data detailed *i)* the economic and technical characteristics of EEM of different types of buildings in the city, and *ii)* the economic and technical characteristics of the PV generation capacity of the city's rooftops.

4.1. Configuration of the initial data

The case study was evaluated by simulating a period of 37 years (T), from 2013 (year of the initial investment) to 2050; with R equal to 4%, and RI equal to 2%. Based on the data groups *i)* and *ii)*, we built a community of Prosumers, a group of Consumers, and a DG system that replaces the operation of Producers (only in the activity of local generation). Figure 3 describes the distribution of these groups, whose characteristics are:

- Prosumers (Psr): hypothetical community of subgroups of Prosumers buildings (nZEB without energy storage) of 2, 3, 4, 5 and 6 floors, whose investment in EEM and PV self-consumption and whose electric energy generated is called Endogenous 1 (Endo_1).
- Consumers (Csr): electric energy consumption sectors of the City (without energy storage), evaluated according to two different approaches (described below).
- DG-Extra: a group of rooftops with investment of PV generation systems on them (PV-Extra), whose generated electric energy is called Endogenous 2 (Endo_2).

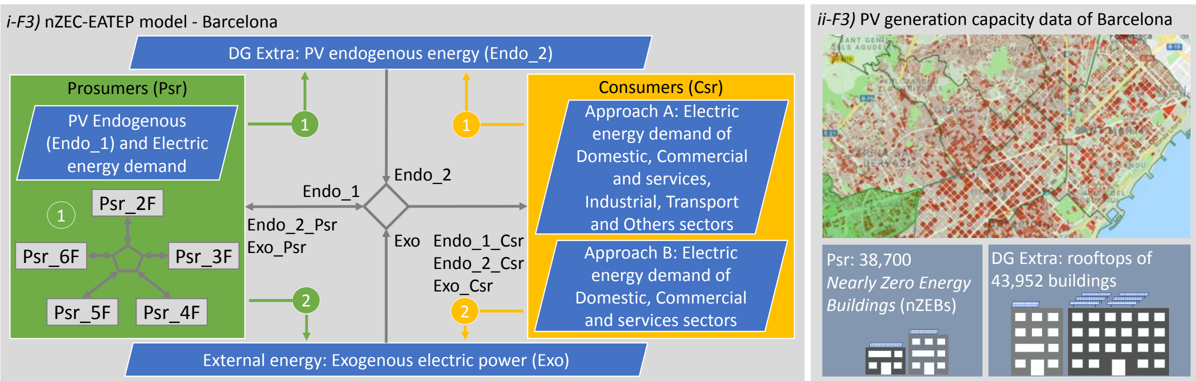

Figure 3. Case study: the Nearly Zero Energy model for Barcelona. Note: i-F3) nZEC-EATEP model – Barcelona, Energy cost 1) eq. (11) and 2) eq. (12); ; ii-F3) PV generation capacity data of Barcelona, Source: Adapted from [64,65]

The evaluated Packages were composed of the EEM packages (Packages-EEM) presented in the [66] (ICAEN-Study), and the PV capacity data of Barcelona presented in [64,65] (PV-Map). The data from these sources were cross-referenced with the relation of the number of floors of the buildings they studied. The objective was to define the initial data on the electric energy consumption of Prosumers and Consumers, the capacity of energy saving and PV self-consumption in the Prosumers, and the extra PV generation capacity corresponding to PV-Extra. Due to the fact that it has not been possible to determine the sector to which the buildings studied in the PV-Map belong, it was assumed that the buildings theoretically characterized in the ICAEN-Study include the buildings presented in this first source. As a result, and as shown in Table 1, for the scope of this paper, a total of 86,626 buildings with suitable PV generation capacity were included in the calculation of the Global Cost of the nZEC-EATEP model. Of this total, buildings from 2 to 6 floors of the ICAEN-Study were assumed as buildings of Prosumers. The remaining number of buildings were considered as buildings of the residential, commercial, industrial and service sectors of Barcelona[4]. Finally, the consumption of initial electric energy assumed for the Consumers was the consumption of this energy vector in the city in 2014 minus the consumption of the Prosumers.

Table 1. Distribution of buildings evaluated in Prosumers, Consumers and PV_Extra. Source: [64–67].

	COD | Subtotal | Total	No. of floors	Type of building[5]	No. of buildings	Electric energy consumption [GWh/Year]
Prosumers	2F	2	A, B and C	12,463	61.787
	3F	3	D	6,238	41.853
	4F	4	I	4,842	245.457
	5F	5	E and H	7,082	339.516
	6F	6	F and G	8,075	274.779
	Subtotal	N/A	N/A	38,700	969.363
Consumers	Approach A	N/A	N/A	N/A	5,771.847
	Approach B	N/A	N/A	N/A	3,225.927
PV_Extra	N/A	No data	N/A	N/A	N/A
	N/A	1	N/A	2,135	N/A
	N/A	7	N/A	5,564	N/A
	N/A	8	N/A	3,606	N/A
	N/A	9	N/A	3,266	N/A
	N/A	≥10	N/A	3,636	N/A
	Subtotal	N/A	N/A	43,952	N/A
Total, Approach A		N/A	N/A	82,652	6,735.24
Total, Approach B		N/A	N/A	82,652	4,189.32

[4] The data on the number of buildings determined for the Prosumers are consistent with the Census 2011 of Spain in Barcelona. See *Buildings with houses according to floors above ground by districts. 2011* [67].

[5] Type of buildings:

- Single family detached house: A, built before 1951; B, built between 1951 and 1980; C, built between 1981 and 1990; D, built after 1990.
- Multi-family building: E, built before 1951; F, built between 1951 and 1980 with collective boiler; G, built between 1951 and 1980 without collective boiler; H, built between 1981 and 1990; I, built after 1990.

4.2. Packages evaluated

The initial data of the Packages-EEM obtained for the Prosumers are presented in Table 2, and the Components that make up these Packages are as follows. The number in brackets is the number of years of useful life with which they were evaluated.

- Package 1 (Pg 1): Exterior façade insulation (50 years) + interior roof insulation (50 years) + PVC windows and low emissive glass (N/A).
- Package 2 (Pg 2): Interior façade insulation (50 years) + interior roof insulation (50 years) + PVC windows and low emissivity glass (N/A).
- Package 3 (Pg 3): Façade insulation in the chamber (50 years) + interior cover insulation (50 years) + PVC windows and low emissive glass (N/A).
- Package 4 (Pg 4): Exterior façade insulation (50 years) + exterior covered insulation (50 years) + PVC windows and low emissivity glass (N/A).
- Package 5 (Pg 5): Integral rehabilitation; EPS 2.36 inches exterior façade insulation (50 years), MW 3.15 inches interior cover insulation (50 years), boiler renovation (16 years), PVC frame windows and 4/16/4 BE glass (N/A).
- Package 6 (Pg 6): Low cost measures; Adhesive tapes and elastic putty (10 years) + DHW aerators and flow reducers (30 years) + LED lighting (20 years).

Table 2. Initial data of EEM for the evaluated Packages. Note: The initial investment cost only refers to the cost of energy rehabilitation. Source: [66]

Item	Prosumer	Packages					
		Pg 1	Pg 2	Pg 3	Pg 4	Pg 5	Pg 6
Energy savings [%]	2F	43.97	19.2	NA / NS	NA / NS	53.73	6.43
	3F	35.5	15.5	15.1	36.1	44.6	6.2
	4F	31.6	14.3	13.7	32.1	41.6	6.8
	5F	41.4	18.75	NA / NS	41.8	51.1	6.95
	6F	47.25	20.7	21.5	47.6	59	7.35
CII_EEM [M€]	Total	2,348.626	1,971.504	1,364.605	2,192.395	2,209.692	52.547
CM_EEM [M€/Year]	Total	36.228	20.260	34.566	36.228	36.228	36.228

Regarding the PV generation capacity of the buildings selected from the PV-Map, Table 3 presents the initial data that make up the six Packages which have been evaluated. This study uses panels of 270W of 2m^2 and generated energy calculated as a mean value 1,250 kWh/kWp·Year.

Table 3. Initial data of PV systems for the evaluated Packages. Source: [65]. Notes: *Endo_1; **Endo_2; ***Total Endo.

Generation	Useful surface [km^2]	Power [MW]	Generation capacity [GWh/Year]	CII [M€]	CM [M€/Year]
Prosumers	1.924	181.823	227.301*	636.443	8.835
PV_Extra	3.307	312.509	390.665**	1,093.861	10.641
Total	5.231	494.332	617.966***	1,730.304	19.476

4.3. Tariff scenarios and energy consumption approaches evaluated

4.3.1. Tariff scenarios

We evaluated the nZEC-Model of Barcelona using three electric tariffs access to the grid in Spain, presented in [66,68], and the prices of energy in the Iberian market presented in [69]. These tariffs include a fixed charge and a variable charge for energy, which are different for Consumers and Prosumers. In the case of the latter, the fixed charge covers the bidirectional operation of the import and export of electricity. The future value of these access tariffs was calculated using an annual evolution rate (RX) of 1.575%, resulting from the average of the Consumer price index (CPI) for the period 2017-2022 in Spain. Regarding the price of energy, we use the hour profile of a model year built with the average of the prices of the period 2014-2017.

For Prosumers, as residential buildings, low voltage and power tariffs (<10 kV and ≤10 kW) were used, assuming an access power of 4.6 kW. This value is in accordance with the average consumption of the dwellings of the buildings characterized in the ICAEN-Study. In Scenario 1 (S1) a flat tariff was used. In Scenario 2 (S2) a tariff of two intraday periods of hourly discrimination was used. And in Scenario 3 (S3) a tariff of three periods of discrimination was used[6]. Table 4 presents the values of these tariffs in their power and energy charges. For Consumers, tariffs with and without periods of hourly discrimination of power access of less than 1 kV and up to 36 kV and with a lower power of 10 kW and up to 450 kW were used. In each of these tariffs we assume a hypothetical access power to calculate a single access power to the grid of 11.8167 kW for all buildings of the Consumers. Because the objective of this paper was to study the economic performance of Prosumers, the same electric energy tariff was used for the Consumers in the three scenarios evaluated. Table 5 presents the value of the power and energy charges calculated for Consumers.

Table 4. Tariffs of electric energy used for Prosumers in each of the scenarios evaluated. Source: [68]. Note: *Denomination used in Spanish electric system; Winter (W); Summer (S).

Scenario	Tariff*	Period (Hours)	Power Charge [€/Year]	Energy Charge [€/kWh]
1	2.0A	Flat	174.999759	0.044027
2	2.0DHA	P1 (W: 12-22; S:13-23)	174.999759	0.062012
		P2 (W: 22-12; S:23-13)	174.999759	0.002215
3	2.0DHS	P1 (13-23)	174.999759	0.074568
		P2 (23-1)	174.999759	0.017809
		P3 (1-7)	174.999759	0.006596

[6] The tariff of three periods of hourly discrimination, called *super-valley*, was designed in the Spanish electricity market with the purpose of promoting the introduction of the electric vehicle. This tariff allows, at a low cost, users to recharge the batteries of this type of vehicle at night, after 10 or 11pm and on into the early hours of the morning.

Table 5. Tariffs of electric energy used for Consumers in all scenarios evaluated. Note: Tariffs and access powers assumed, according to the denomination of the electric market in Spain: 2.0A [4.6kW], 2.0DHA [4.6kW], 2.0DHS[4.6kW], 2.1A [10.35kW], 2.1DHA [10.35kW], 2.1DHS [10.35kW], 3.0A [15kW], 3.1A [26kW]. Source: Based on [70].

Winter			Summer		
Period (Hours)	Power Charge [€/Year]	Energy Charge [€/kWh]	Period (Hours)	Power Charge [€/Year]	Energy Charge [€/kWh]
1-2	455.5225946	0.022218	1-2	455.5225946	0.022218
2–8	401.9505098	0.017808	2–8	401.9505098	0.017808
8–10	401.9505098	0.020611	8-9	401.9505098	0.020611
10-13	455.5225946	0.022218	9-10	443.4905825	0.021230
13-14	455.5225946	0.037364	10-11	455.5225946	0.022218
14–19	455.5225946	0.051554	11-12	489.0270513	0.022415
19-20	489.0270513	0.051752	12-13	513.0910991	0.023189
20-23	513.0910991	0.052525	13-14	513.0910991	0.038335
23-24	513.0910991	0.037378	14-16	513.0910991	0.052525
24-1	455.5225946	0.022218	16-17	489.0270513	0.051752
-	-	-	17-24	455.5225946	0.051554
-	-	-	24-1	455.5225946	0.022218

4.3.2. Energy consumption approaches

The nZEC-Model to Barcelona was evaluated according to three different approaches based on the consumption of electric energy of the city. The first of these approaches (Approach A) was configured based on the consumption of the domestic, commercial and services, industrial, transport and other sectors. The second approach (Approach B) was configured based on the consumption of the domestic and commercial sectors and services (62.2% of total consumption). And the third approach (Approach C) focused on the consumption of the Prosumers, thus analysing the investment towards nigh zero-energy consumption of a community of buildings within the city.

4.4. Profiles of electric energy consumption and PV generation designed

The profiles of electric energy consumption and PV generation that were used in the model were constructed based on the data of 2014-2017 hourly intervals of mainland Spain, presented in [69]: the total consumption to construct the profile of the Consumers, and consumption data in low voltage to construct the profile of the Prosumers.

5. Results

5.1.1. General results

Taking into account that this economic evaluation addressed the utilization of the PV generation capacity of 34.7% of the Barcelona's rooftops (82,652 of a total of 238,213 included in the Map), and the investment in EEM and PV self-consumption (with capacity of export of surpluses to the grid) in 17% of its buildings, the main results are:

- On the basis that the city consumes between 6,700 and 7,000 GWh of electricity per year, it has the capacity to reduce the primary energy demanded by between 3.41 and 9.68%. This can cause a reduction of between 4.16% and 12.25% in energy costs, and between 5.16% and 11.43% in CO_2 emissions.
- The investment required to generate these savings is 1.25 and 1.32 times the energy costs of the city over a period of 37 years, taking into account that this investment covers the initial value and the replacement of the technical components of the packages during the same period.
- The Package of general rehabilitation of the studied buildings (Package 5) obtains the best results in terms of reduction of primary energy consumption and CO_2 emissions, as well as in energy costs.
- The low-cost Package (Package 6) obtained the Optimal-Cost from the Global Cost study due to its low investment and maintenance costs. But in terms of energy costs, the general rehabilitation Package (Package 5) allows for better results (almost 8% less).
- The scenario of tariffs for three periods of intraday and hourly discrimination gave a better result for the Global Cost.
- Regarding the results of the approach of the Prosumers (Approach C), this community can reduce its primary energy consumption by up to 51%, up to 70% of the CO_2 emissions, and between 32% and 71.25% of its energy costs.

5.1.2. Consumption and generation profiles

In the graphics *i-F4)* and *ii-F4),* Figure 4 presents the profiles resulting from the average of the 37 years of economic evaluation of the consumption of Consumers and Prosumers and the generated endogenous energy. In the case of the Consumers, their consumption is presented in the approaches A and B. In that of the Prosumers, the consumption profile of the Reference Case is presented and after the savings achieved with the six Packages are evaluated. From top to bottom, these Packages are ranked from lower (Package 6: low cost measures) to higher savings achieved (Package 5: complete building rehabilitation). The same graphs present the average profiles of generation Endo 1 (Prosumers only), Endo 2 (PV_Extra only), and the sum of these two (T. Endo). The graph *ii-F4)* presents the daily profiles of consumption and generation. As shown here, the Endo 1 energy, at its generating peak, (between 12 and 3pm) exceeds the second consumption peak of the Prosumers with Packages 4, 1 and 5. In total during the evaluation period, Endo 1 covered 22.37% of the demand of the Prosumers Reference Case, and Endo 2 covered 6.73%.

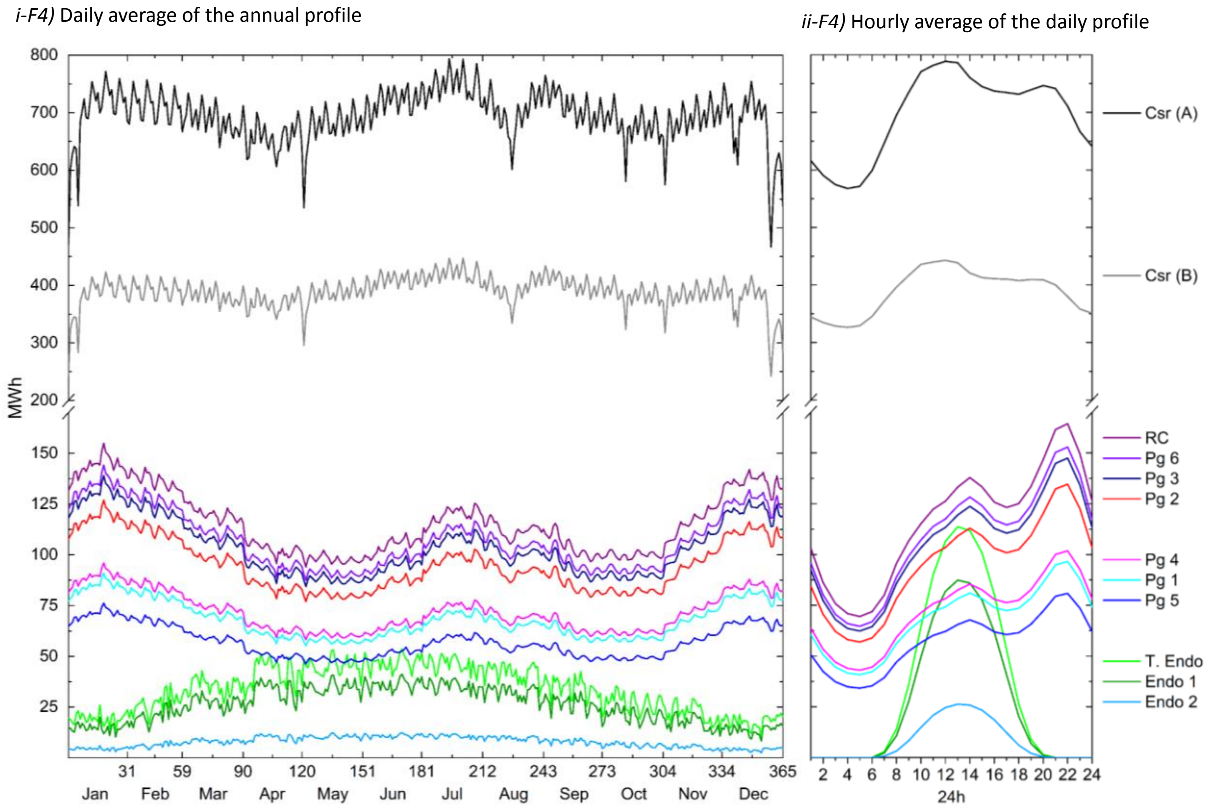

Figure 4. Profiles resulting from the average of the 37 years of economic evaluation. Note: Consumers (Csr); Reference Case (RC); Approaches A (A) and B (B); Package 6 (Pg 6): Low cost measures; Package 5 (Pg 5): Complete building rehabilitation.

5.1.3. Global Cost and Optimal-Cost

Figure 5 presents the results of the Global Cost (CG(T)) and the Global Primary Energy Consumed (EGC(T)) in the graphical format of the Optimal-Cost. Graph *i-F5)* presents the results of the approaches A and B, and Graph *ii-F5)* presents the results of approach C. In the two graphs the packages are ordered from right to left according to the consumption of primary energy of the nZEC-Model. In these results, with the exception of Package 2, the Global Cost increases in with energy saving due to the packages costs. Approaches A and B share the same results in Global Investment and Running Costs, which were not accounted for in their respective reference cases. The difference in the Global Cost between these two approaches is therefore due to the energy costs: Approach A analyses the coverage of the electric energy demand of the whole city, and Approach B focuses on a demand 37.8% lower (energy consumption of the domestic and commercial sectors and services).

The energy saving obtained with the packages of EEM and PV self-consumption is crucial in reducing the Global Cost of the model. Moreover, with each electric energy tariff scenario each Package gives a different Global Cost: the lowest result is obtained with the tariff of three periods of hourly discrimination (S3), followed by the results of the tariff with two periods (S1). However, in the Reference Case the two-period tariff allows obtaining the lowest Global Cost.

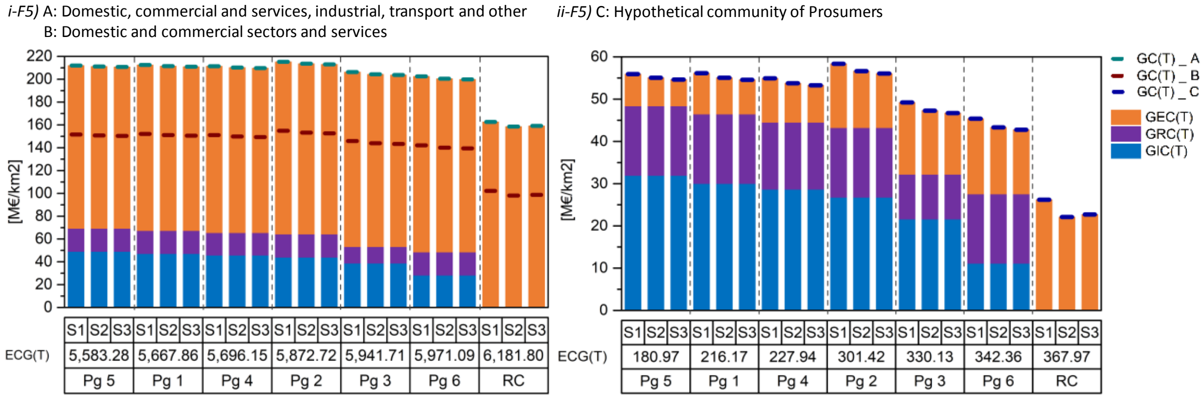

Figure 5. Optimal-Cost graphics. Notes: T = 37 years; Reference Case (RC); Global Cost (CG(T)); Global Primary Energy Consumed (ECG(T)) [GWh_PE/km2].

5.1.4. Analyses of the energy, economic and environmental benefits

To analyse the benefits obtained with the Packages in more detail, the Effect-Index [23] indicator was calculated. This indicator is the sum of the energy, economic and environmental benefits normalized between 0 and 1. Therefore, its result is higher if the energy saving and reduction of CO_2 emissions are greater and energy costs are lower. Figure 6 compares the results of Effect-Index with the results of the Global Energy Cost (CEG(T)). Unlike the approaches A and B, in the approach C the lower CEG (T) obtained in the scenario with three periods of hourly discrimination (S3) allows obtaining a greater result in the Effect-Index. This is because in this approach the economic results of the energy exported by the Prosumers stand out without the results of the Consumers.

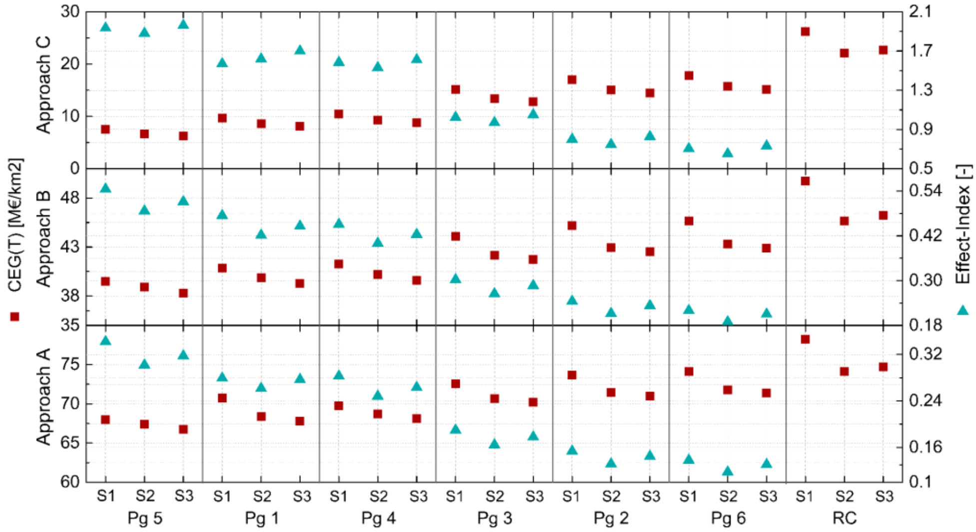

Figure 6. Global Energy Cost (CEG(T)) and Effect-Index by Packages and Scenarios in each evaluation approach.

5.1.5. Analysis of tariffs on the cost of energy

As seen above, the Package of general rehabilitation (Package 5) obtained the most outstanding results in the Optimal-Cost, and the greatest economic benefit was obtained in the scenario with three periods of hourly discrimination (S3). From this, Figure 7 presents the annual average hourly energy performance profile of this package. With a ratio between exported and imported energy (EP/EI) of 0.31 in all scenarios, Scenario 3 presented a ratio between costs of exported and imported energy (CE/IR) of 0.34 versus 0.26 and 0.31 in Scenarios 2 and 1 respectively. The greatest volume of income from the export of energy (negative costs) occurred in the months of the middle of the year, when the energy surpluses of self-consumption are higher.

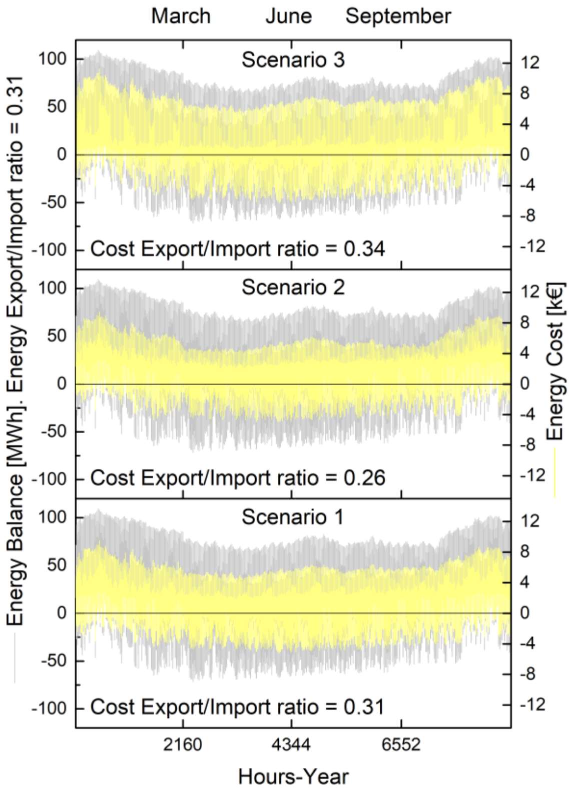

Figure 7. Hourly average of the annual profile of the energy balance vs energy costs (positives and negatives) of the Prosumers community (approach C) with the energy savings of the Package 5 in the tariffs scenarios 1 (S1), 2 (S2) and 3 (S3).

Figure 8 extends this analysis by presenting the hourly average of the daily profile in winter and summer, indicating the start of the intraday periods of tariffs: P1 (peak), P2 (valley) and P3 (super-valley). In the tariff without hourly discrimination (S1), graph *i-F8)*, the costs (positives and negatives) follow the same curve as the energy balance: their ratios EP/EI and CE/IR are equal to 0.27. Compared to S1, S2 and S3, graph *ii-F8)*, handle different energy and cost balances because the periods of hourly discrimination are different in winter and summer. In these two scenarios, the energy balance in winter obtained an EP/EI equal to 0.1, and of 0.52 in summer; values that differ due to the variation of the energy import depending on the PV generation between these two seasons. However, the EC/IR is higher with the tariffs of three periods of hourly discrimination that were studied in S3: 0.09 in winter and 0.64 in summer, compared to 0.08 in winter and 0.43 in summer in S2. As shown in the graph, this result is due to the fact that there is a marked difference in the S3 between the costs of the morning, those of midday, and those of the evening.

i-F8) S1: Flat tariff *ii-F8)* S2: Peak and Valley intraday periods; S3: Peak, Valley and Super valley intraday periods

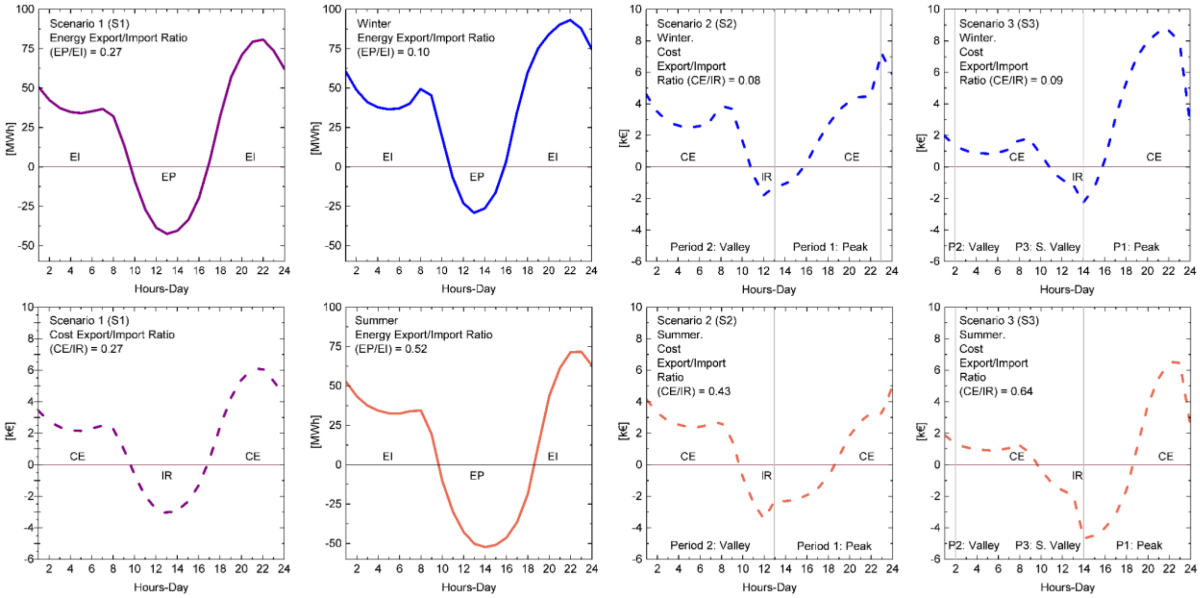

Figure 8. Hourly average of the daily profile of the energy balance and the energy costs (positives and negatives) of Prosumers community (approach C) with the energy savings of the Package 5 in the tariffs scenarios 1 (S1), 2 (S2) and 3 (S3).

2. Conclusions

Faced with the emission of greenhouse gases due to covering the energy demand of cities with fossil energy resources, the urban energy transition is crucial in order to be able to achieve climate objectives against global warming. This transition process aims to use renewable energy resources in cities while reducing the consumption of external energy resources of fossil origin.

Although each city has different conditions, any use of local energy resources will reduce the consumption of primary external energy of fossil origin. However, investment, maintenance and energy costs are yet to be determined. This is the basis upon which the model proposed in this paper and the study from which its results are presented. In this context, this paper proposes a novel model to technically and economically evaluate the energy self-sufficiency of these urban areas. This model contributes by proposing the scalability in the simulation of Nearly Zero Energy Buildings up to Nearly Zero Energy Cities scale.

Using public data from Barcelona, this model was applied to the self-consumption study of this city. The objective was to analyse the scope of the investment in the PV self-consumption of buildings in order to promote the creation of communities of Prosumers within the cities. In order to do so, we studied the investment of six packages of energy rehabilitation measures and PV self-consumption in 38,700 buildings (2-6 floors), the investment in PV systems in the remaining 43,952 buildings

(53.18%), and we simulated 37 years (2013-2050) of the energy performance of this city. The results indicated that the existence of communities of nearly zero energy buildings sharing energy as Prosumers helps reduce primary energy consumption and CO_2 emissions of the city. Regarding the results obtained in the specific evaluation conditions of the nZEC model for Barcelona, it is concluded that the general rehabilitation Package (Package 5) presents better results in terms of reduction of primary energy and energy costs and the tariff of three periods of intraday discrimination allows greater benefits for PV self-consumption than the flat tariff and the two-period tariff.

Within the process of energy transition, urban electrical systems go through a stage of digitalization that seeks to make their operation more flexible by involving consumers in the management of demand. Likewise, the urban energy transition includes new services in the cities, such as the aggregation of demand and the participation of Producers in distributed generation. By taking advantage of the Nearly Zero Energy Cities evaluation model presented here, the inclusion of these new characteristics of the electric urban systems will form the basis of any future work in the research area of this paper.

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